Blobby cross-field plasma transport in tokamak edge

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Abstract. Recent studies suggest rather fast radial plasma transport in tokamak scrape off layer (SOL). Moreover, it seems that this transport has not diffusive but convective-like features. One of the plausible mechanisms of this fast convective SOL plasma transport can be associated with plasma "blobs" [1] seen also in experiments [2]. In this report we present the results of our investigations of different aspects of blobby non-diffusive transport in the SOL.

Analytic theory. The ∇B drift of charged particles in a tokamak magnetic field results in plasma polarization and, correspondingly, the $\mathbf{E}\times\mathbf{B}$ plasma flow. This effect of $\mathbf{E}\times\mathbf{B}$ flow becomes rather strong in the SOL due to effective "sheath resistivity" [3] when the plasma contacts the divertor target. For $T_i = 0$ and constant T_e we have the following equation for the SOL plasma dynamics accounting for these effects

$$\rho_s^2 \nabla_\perp \cdot \left(n d_t \nabla_\perp \varphi \right) + \rho_s (2C_s / R) \partial_y n = (2C_s / L) n\varphi, \qquad (1a)$$

$$d_t n = -2C_s \left(n - n_0(x) \right) / L, \qquad (1b)$$

where $d_t(...) = \partial_t(...) + \mathbf{V}_{E\times B} \cdot \nabla(...)$, $n_0(x)$ describes the plasma ionization source. In the case where both leakage to the plate and inertial term are small, we find blobby solutions of (1) in the form of traveling wave. The radial velocity of these blobs can be estimated as follows [1] $V_b \sim C_s (\rho_s / \delta_b)^2 (L / R)$, where δ_b is the width of the blob, which is in a reasonable agreement with recent experimental data [2].

However, we neglected the leakage of the plasma blob along the magnetic field line to the targets, which implies that our estimates should satisfy $\tau_\| \sim L_\| / C_s > \tau_\perp > \delta_b / V_b$. It results in the following restrictions

$$V_b > (V_b)_{min} \sim C_s (\rho_i / R)^{2/3} (\pi q)^{-1/3} \sim 150 \text{ m/s}, \qquad (2a)$$

$$\delta_b < \delta_{max} \sim C_s \left\{ (\pi q)^2 R \rho_i^2 \right\}^{1/3} \sim 2.5 \text{ cm}, \qquad (2b)$$

where we assume q~3 and C-Mod/DIII-D edge plasma parameters. But, we also neglected vorticity impact which reduce the effects of ∇B polarization current. It implies $(\rho_i / \delta_b)^2 V_b / \delta < C_s / L_\|$, causing the following restrictions

$$V_b < (V_b)_{max} \sim C_s (\rho_i / R)^{2/5} (\pi q)^{-1/5} \sim 2000 \text{ m/s}, \qquad (3a)$$

$$\delta_b > \delta_{min} \sim C_s \left\{ (\pi q)^2 R \rho_i^4 \right\}^{1/5} \sim 0.5 \text{ cm}. \qquad (3b)$$

We notice that the difference in estimates (2) and (3) for C-Mod and DIII-D conditions is small even though the C-Mod and DIII-D parameters differ significantly.

Taking into account the leakage, blobs can propagate in radial direction at the distance $\Delta_b \sim V_b \tau_{||} \sim V_b L_{||} / C_s$. As a result we find maximum radial distance the blobs can propagate on before plasma leaks to the targets

$$\Delta_b < (\Delta_b)_{max} \sim \left\{\rho_i^2 R^3 (\pi q)^4\right\}^{1/5} \sim 30 \text{ cm}. \qquad (4)$$

The resistivity effects increase both Δ_b and V_b by $\sigma = 1 + \zeta \frac{m}{M} \frac{\nu_e L_{||}}{C_s} \sim 1 + \zeta \sqrt{\frac{m}{M}} \frac{\pi q R}{\lambda_e}$.

The ionization of neutrals [2] or recombination processes may alter blob's dynamics. But for standard tokamak SOL parameters this effects seems to be weak. However the blob's plasma in-flight recombination can be important ingredient of blob dynamics in linear divertor simulators [4], where neutral gas density is high and plasma cooling followed by recombination is, accordingly, fast.

Modeling of the blobs with turbulence codes. Both 3D modeling with code BOUT [5] and 2D modeling with reduced model of the SOL plasma turbulence similar to Eq. (1) were applied to study the evolution of artificially generated density blobs [6]. For example, in Fig. 1 we show the results of the simulation of blob dynamics in the SOL with 3D plasma turbulence code BOUT . Similar results (see Fig. 2) were found with the reduced 2D model. We also show that votricity effects suppress radial propagation, Fig. 3.

Macroscopic transport modeling of the edge plasma transport in tokamaks. We apply and implement into the 2D edge transport code UEDGE a plasma transport model which includes both diffusive and outward convective terms for cross-field plasma particle flux. This model was used to model the DIII-D discharges. The results of the modeling confirm the crucial importance of convective transport for edge plasma. We demonstrate that convective transport has equally important effects on averaged plasma characteristics in both main chamber and divertor. Modeling of DIII-D discharges with mixed anomalous diffusion/convection model for radial plasma transport [7] allows us successfully match experimental data which could not be matched otherwise. As an example, in Fig. 4 we show H_α intensity along different viewing chords in DIII-D tokamak. Recall that for tokamak conditions H_α represents the plasma ionization source and, therefore, indicates plasma particle losses. Inclusion of convection leads to enhanced recycling of plasma on the wall of main chamber. As one sees, it is not possible to fit the most outward chords without invoking convective plasma transport. It appears to be true for both L and H mode regimes.

On impurity transport in edge plasma. Usually in the modeling with 2D transport codes like UEDGE impurity transport is described by diffusion process with some *ad hoc* diffusion coefficient. Meanwhile based on recent findings of strongly intermittent effects in edge plasma turbulence, it is obvious that diffusive model of impurity transport is, at least, incomplete. Moreover, if we adopt the blobby paradigm for SOL plasma turbulence, then very much different from simple diffusive, picture of impurity transport in the SOL would emerge. First we notice that while the blobs (hills on plasma density 2D poloidal profile) ballistically move to the wall, the dips (valleys on plasma density 2D poloidal profile) moves to core plasma, Fig. 5. Such features are observed in our 2D modeling [6] and have been seen experimentally near the separatrix [2] where it is easy to diagnose dip's motion. Then qualitatively impurity transport in the SOL might be described as follows (see Fig. 6). High Z ionization states of impurity move from hot core to the wall being entrained in the blobs. Recall that blobs carry the most of plasma flux to the wall. When blob hits the wall, neutral impurity atoms/molecules, being sputtered from the wall, fly to the plasma and, finally, are ionized in some vicinity from the wall, Fig. 6a. Those which are ionized within the blobs will be immediately carried to the wall by the blob motion and will not contribute to core plasma contamination. But those which are ionized within the dips will be carried towards the core plasma, Fig. 6b. Since dip's plasma is cold not many electrons can be stripped from impurity. Thus, qualitative picture of impurity transport in the SOL might look like this: high Z ionization states of impurity are convectively transported by the blobs from the core to the wall, while low Z ionization states are transported by the dips from the wall to the core. This model can explain fast penetration of impurity from the wall to the core seen in experiment.

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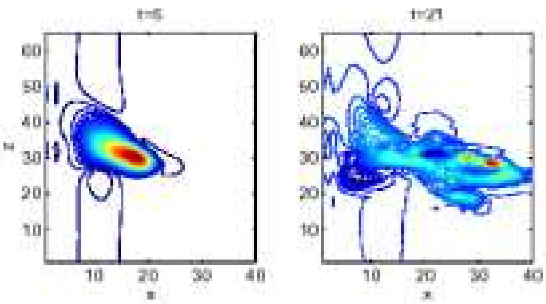

Fig. 1. The plasma density contour plots (poloidal projection) from 3D BOUT simulations.

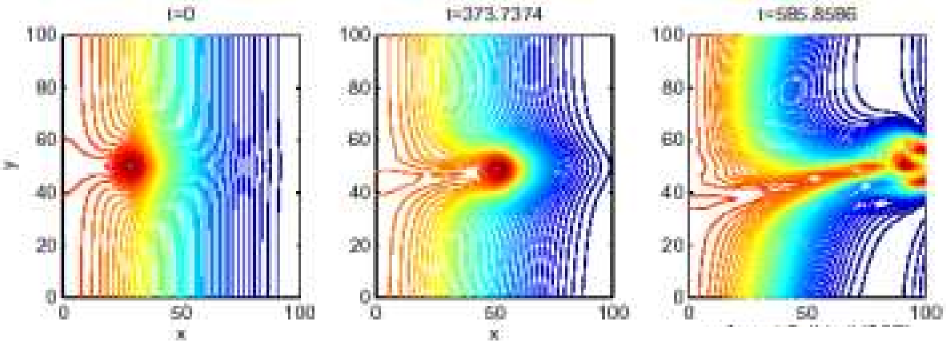

Fig. 2. The plasma density contour plots (poloidal projection) from 2D model.

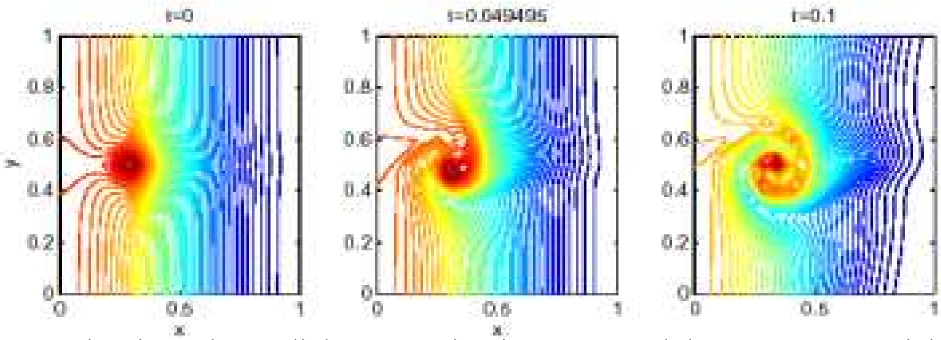

Fig. 3. Same as in Fig. 2, but radial propagation is suppressed due to strong vorticity effects.

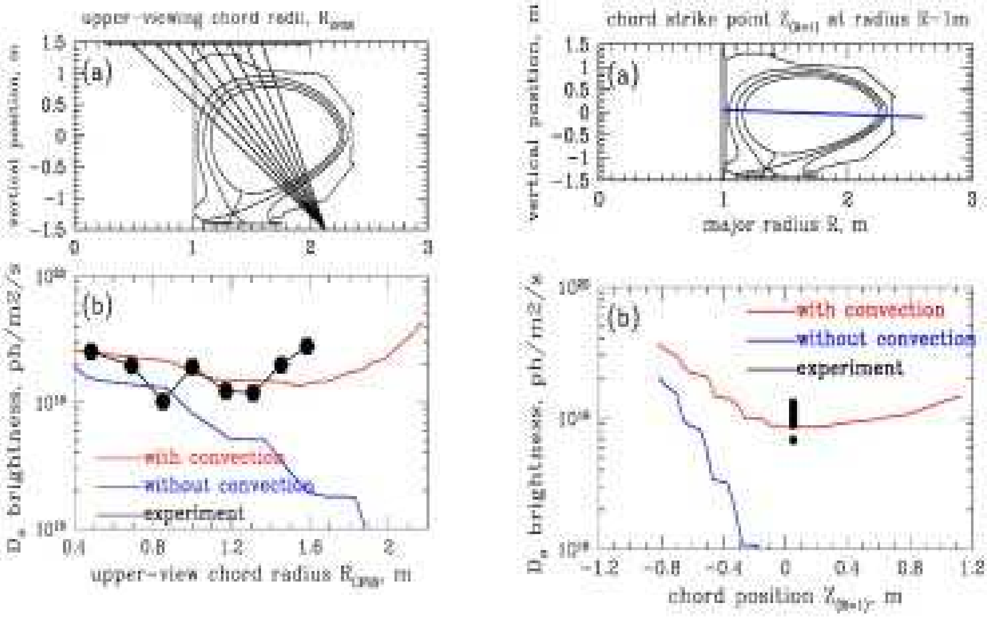

Fig. 4. H_α intensity along different viewing chords in DIII-D tokamak.

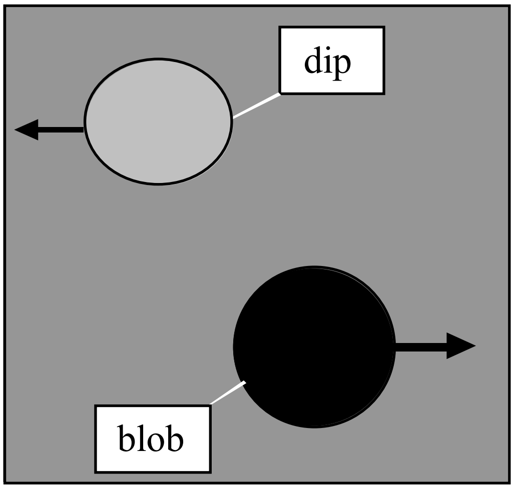

Fig. 5 Blob's and dip's convection in the SOL plasma.

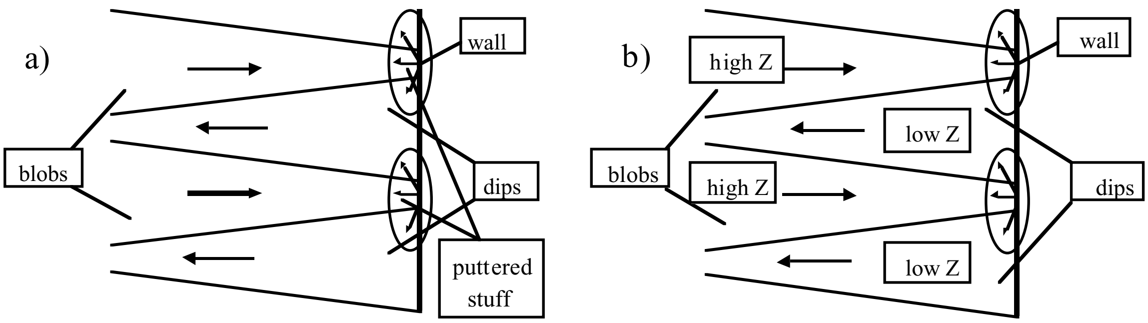

Fig. 6 Schematic picture of the plasma and impurity turbulent flows near the wall.